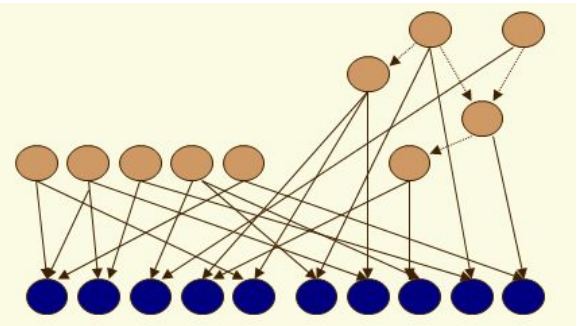
From High Speed Train to Bayesian Network



Yangdong Steve Deng
School of Software
Tsinghua University

Outline

- **The High Speed Train Sustainability Problem**
- **Problem Characteristics**
- **Ongoing works**
- **Conclusion**

High-Speed Railways Witness China's Rising Power

- Unprecedented development in the past ~10 years
  - Largest high speed railway network
    - 19,000 KM by 2015 or over 60% of global mileage
    - Link all cities of more than 500,000 people with services of >160km/h
  - Largest high speed train fleet
    - 1800 trains (8 or 16 units each) and will reach 2000 in 2018
  - Largest passenger traffic
    - 1.2 billion in 2015
- Significance
  - Fundamentally changed how Chinese people travel and live
  - Stimulate China exportation business
  - A strategic tool to expand China's political reach

Safety, Safety, and Safety!

Eschede Derailment
101 people died and ~100 heavily injured, >50M€
(Germany, 1998.6.3)

Yongwen Route Collision
40 people died and 172 heavily injured, >200MRMB
(China, 2011.7.23)

Santiago de Compostela Derailment
79 people died and 180 heavily injured, >30M€
(Spain, 2013.7.24)

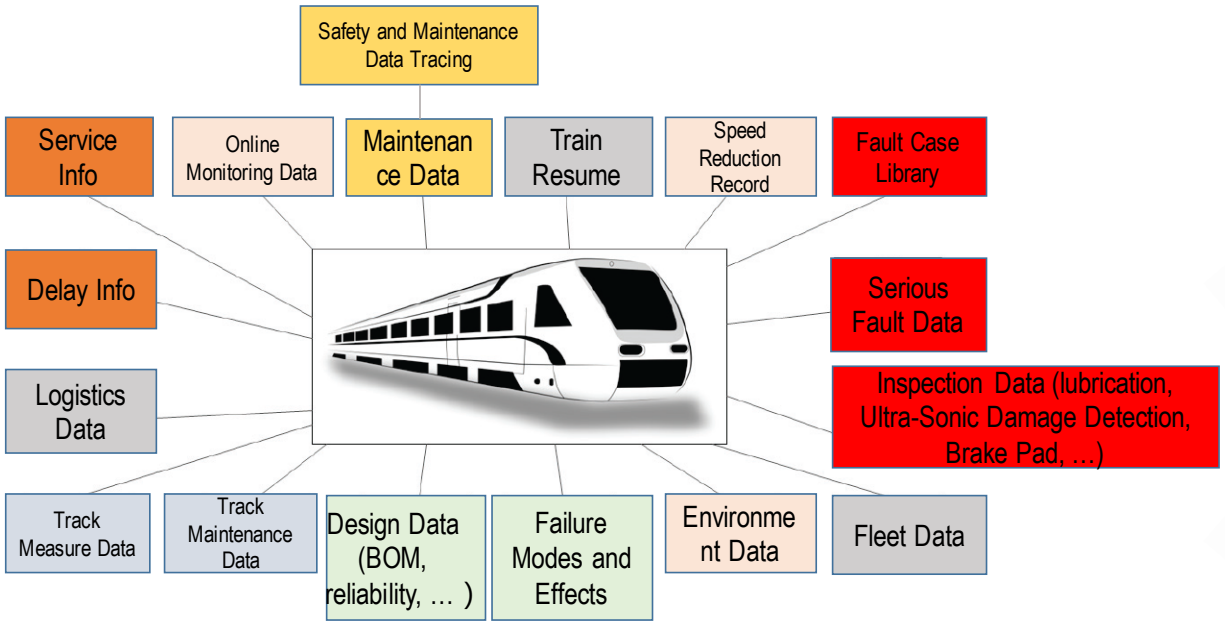
How to Guarantee High Speed Train Safety?

- China practice: labor intensive planned maintenance
  - A regular check every 4000KM or 48 hours
    - A maintenance depot typically maintains 30 trains in one night (8 hours)
    - Mechanical checking in the service pitch
      - Manual inspection with a flashlight and a test hammer
  - Online monitoring data
    - Train control system reported detected fault
      - An onboard engineer for emergency processing
    - Manual checking of real-time way-side inspection photos (24-hour per shift)
  - Fault diagnosis by human experience
    - Manual inspection of fault data and history records
- "(We) maintain the most advanced equipment with the most primitive techniques"

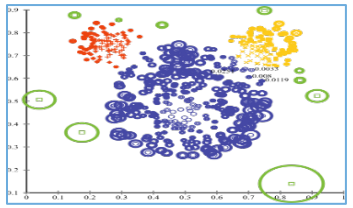
Challenge

- “China High Speed Train Sustainability Problem”
  - The “whatever it takes for safety” approach cannot maintain a sustainable development
    - The overall network is still expanding
    - Shortage for experienced technicians and engineers
    - Railway operators are constantly losing money
  - China high speed railway is facing a switching period
    - Higher fault rate expected after over ten years of operation
  - The current maintenance scheme cannot be ported abroad
    - A strong momentum of exporting high speed railways

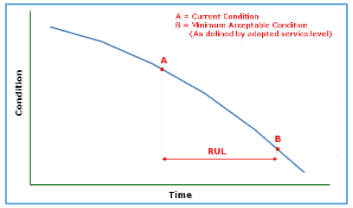
How Can We Address the Challenges?



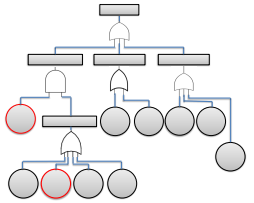
Big Data of High Speed Train



On-line Anomaly Detection



Estimation of Remaining Useful Life



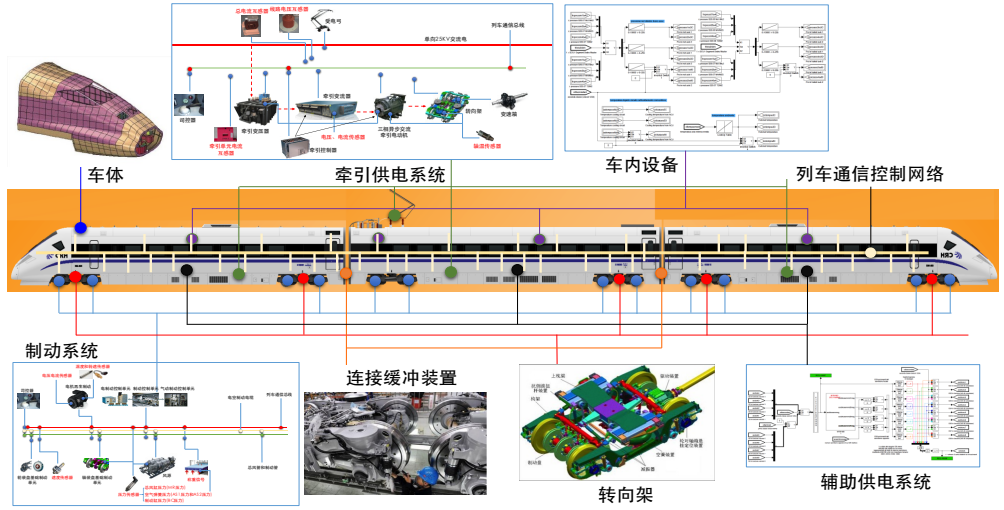
Smart Fault Diagnosis

Outline

- **Introduction: High Speed Train Sustainability Problem**
- **Problem Characteristics**
- **Ongoing works**
- **Conclusion**

High Speed Train – A Sample of Modern Mechatronics

- CRH380 Electric Multiple Unit (EMU)
  - 8 major systems
    - 700K major components
    - >1000 sensors
  - A synergy of complex functionalities
    - Complex interactions in multiple physical domains
    - Mechanical, electrical, electronic, thermal, fluid, …
  - Multiple networks
    - A global control network
    - Many local networks
    - Air pipes

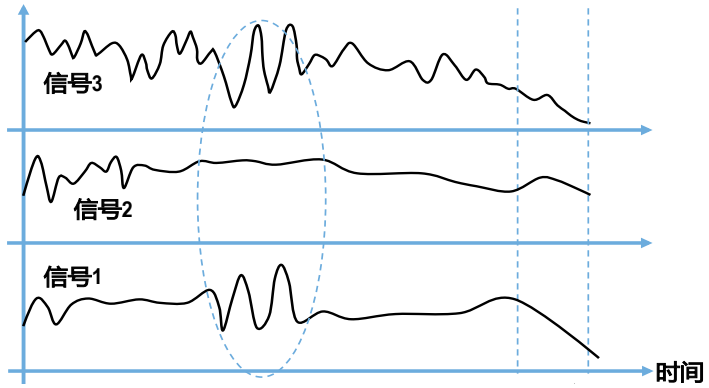


Mechanics Electrical Electronics Thermal Fluid

“Big Data” of High Speed Trains

- Sources of data
  - Online monitoring and fault data (wireless transmitted)
    - A batch from trains in every 15 seconds
    - Train log downloaded after operation
  - Maintenance data (typically manually input Excel forms)
  - Design data (owned by manufacturers)
- Form
  - Monitoring data as multiple temporal sequences
  - Fault log (data dump)
  - Unstructured manual record (text and Excel)
- Data generation speed
  - 5TB/month

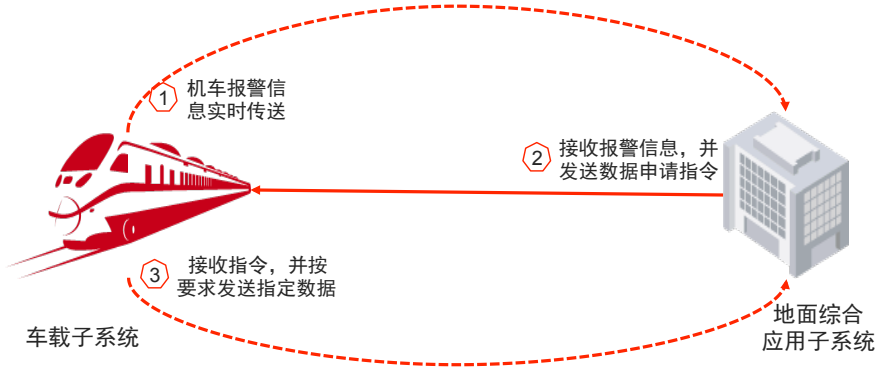
No uniform time stamp



序号	日期	故障状况	所属系统	故障原因	处理方法	故障详细分类
1	1月2日	7:20 109110在白云公园上行对标-40cm，屏蔽门没有联动	ATP/ATO			对标不准
2	1月2日	12:30 1209次（2A035036）在嘉禾望岗下行司机开钥匙后信号屏出现黑屏、ATO灯不亮、车门自动关闭，行调组织司机复位ATP以RM模式动车后恢复正常	ATP/ATO	ATP的B通道5V电源板块工作不稳定，更换后恢复正常。		电源板
3	1月2日	12：40分，广州南站TC572区段红光带后变粉红光带，逻空后恢复正常	SICAS			轨道电路
4	1月2日	广州南站巡检时RTU有报警信息	ATS		重启RTU后恢复正常	RTU
5	1月3日	13:53 MMI显示大洲出厂线TC572轨道区段红光带，瞬间变为粉红光带，行调通知车站逻空后恢复正常	SICAS	接收端轨旁盒内较为潮湿	更换接收端调谐单元、转换单元	轨道电路
6	1月3日	6:07 列车在江泰路联锁区运营停车点不能自动取消。OCC将故障报通号调度。6:23 经信号人员处理后恢复正常。	ATS			运营停车点不能自动取消
7	1月4日	10:39 2304次（ 8A119120）以ATO模式在白云公园上行对标+50cm，车门正常打开，屏蔽门没有联动打开，司机手动开关屏蔽门后恢复正常， 12:27 2306次（8A119120）以ATO模式在白云公园上行对标-40cm，车门正常打开，屏蔽门没有联动打开	ATP/ATO		更换了同步环线检测板	对标不准
8	1月4日	13:44 2009次（8A107108）以ATO模式在江夏下行对标-40cm，列车没有收到开门使能信号，司机按压4S04（强行开门按钮）给出开门使能信号。后续的0211次（8A101102）、3107次（8A119120）在该处出现同样故障。	ATP/ATO		更换了同步环线报警板	对标不准
9	1月5日	9：45分，江泰路站2趟车上行屏蔽门不能联动关闭。	ATP/ATO	多路接收器CPUB50工作不稳定导致。		屏蔽门不能联动
10	1月5日	15：41，145146车在市二宫上行对标-20cm,屏蔽门不能联动打开。	ATP/ATO	多路接收器CPUB50工作不稳定导致。		屏蔽门不能联动
11	1月6日	11:14 MMI显示南浦联锁区轨旁ATP故障，10秒后自动恢复正常。OCC组织信号人员抢修。期间，洛溪～南洲上行区间的2406次（2A045046）、南浦～洛溪上行区间的4004次（2A039040）及洛溪～南浦下行区间的2705次（8A115116）均出现紧制，行调组织上述列车以RM模式动车后恢复正常运行。	ATP/ATO			轨旁ATP

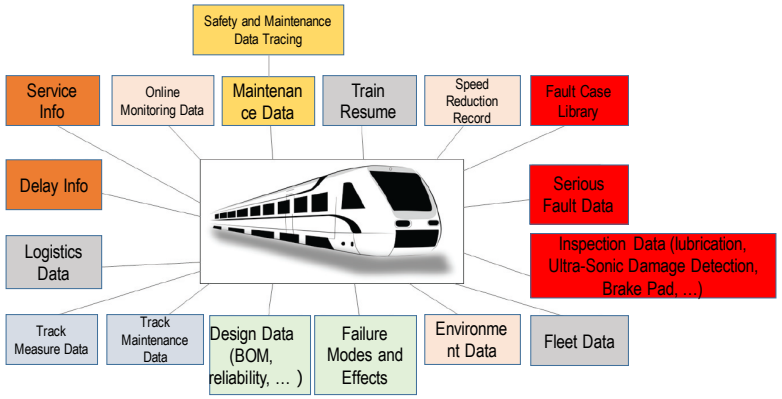
“Big Data” of High Speed Trains cont’d

- Uncertainty
  - Transmission failure and error
  - Ambiguity in manual record
- Fault information is highly sparse
  - A huge number of potential faults
    - ~7,000 types of faults with each having multiple failure modes, ~2,000 critical faults
    - Long tail distribution of faults (No dominant faults)
  - Low fault rate
- Online monitoring data is highly route-related
  - Geographic and climatic conditions
  - But no environment data

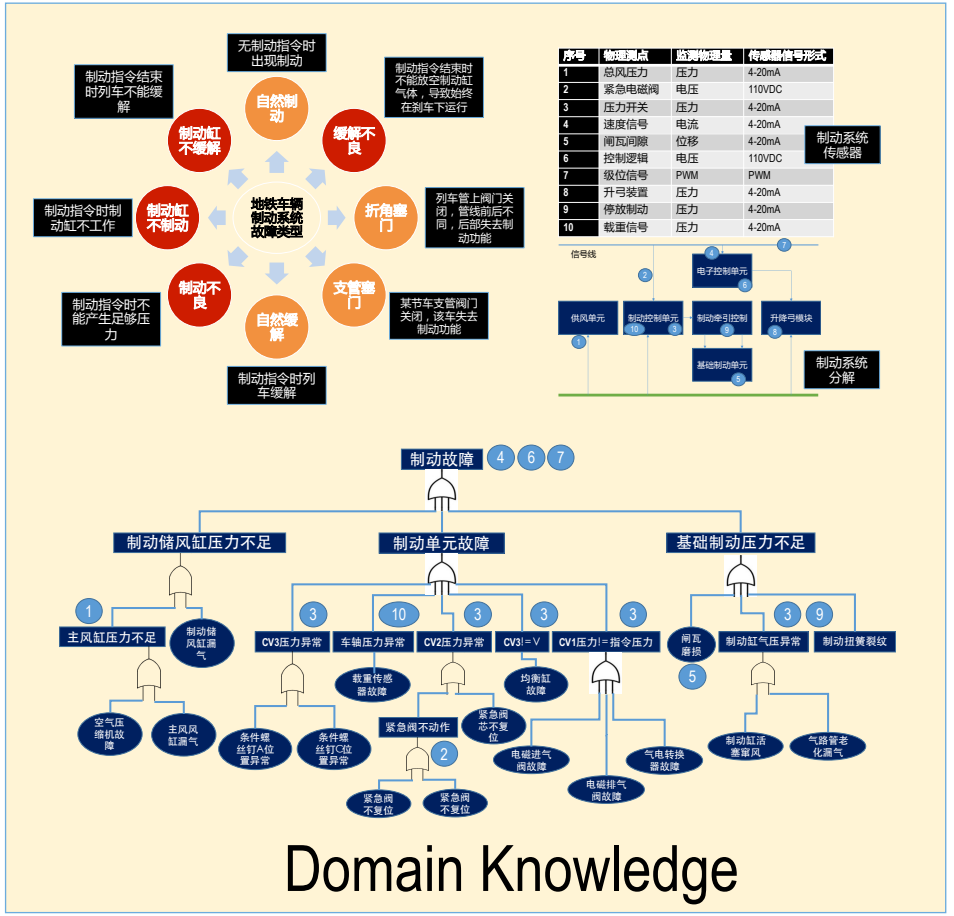


列车数据分类		动力学信号	电学信号	热力学信号	流体力学信号
列控数据	司机指令	列车是否恒速、牵引手柄级位、运营里程、恒速目标速度	列车电制动功率设定值		列车空气制动率
网络设备状态数据		振动	列车通信网络波形、数据帧	设备柜温度	
系统状态数据	牵引传动系统	速度、牵引力、空簧载重、电机转速	网压、网流、牵引用电能量、牵引变流器功率、主变油温、牵引变流器功率、牵引变流器中间电压、电机电压、电机电流	主变压器温度、电机轴承温度、电机齿轮温度、电机定子温度、冷却油温度	
	制动系统	速度	电制动反馈能量、EP阀电流		主风管压力、制动缸压力、空气制动力、工作风缸压力
	辅助供电系统		输入 / 输出电流、电压		
	转向架	振动、横纵向位移		轴温	

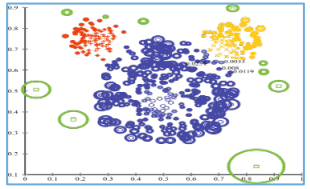
Domain Knowledge: The Bridge



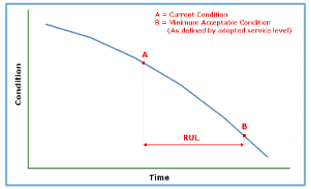
Big Data of High Speed Train



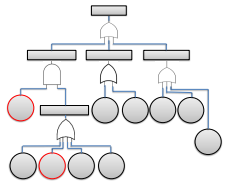
Domain Knowledge



On-line Anomaly Detection



Estimation of Remaining Useful Life

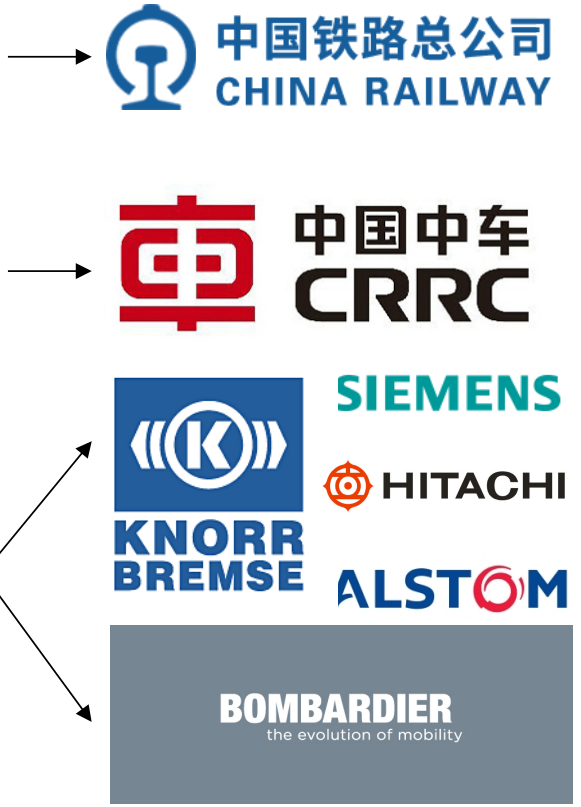


Smart Fault Diagnosis

Big Data Applications

Lack of Systematic Domain Knowledge

- China's unique distributed maintenance system
  - Daily maintenance by China Railway Corporation
    - Railway operators
    - Owner of online monitoring data and fault records
  - Advanced maintenance by China Railway Rolling Stock Corporation
    - Train manufacturers
    - Owner of train-level design data
  - Core equipment imported from foreign manufacturers
    - Owner of part-level design data
- Lack of systematic domain knowledge
  - Still struggling to digest the imported technology

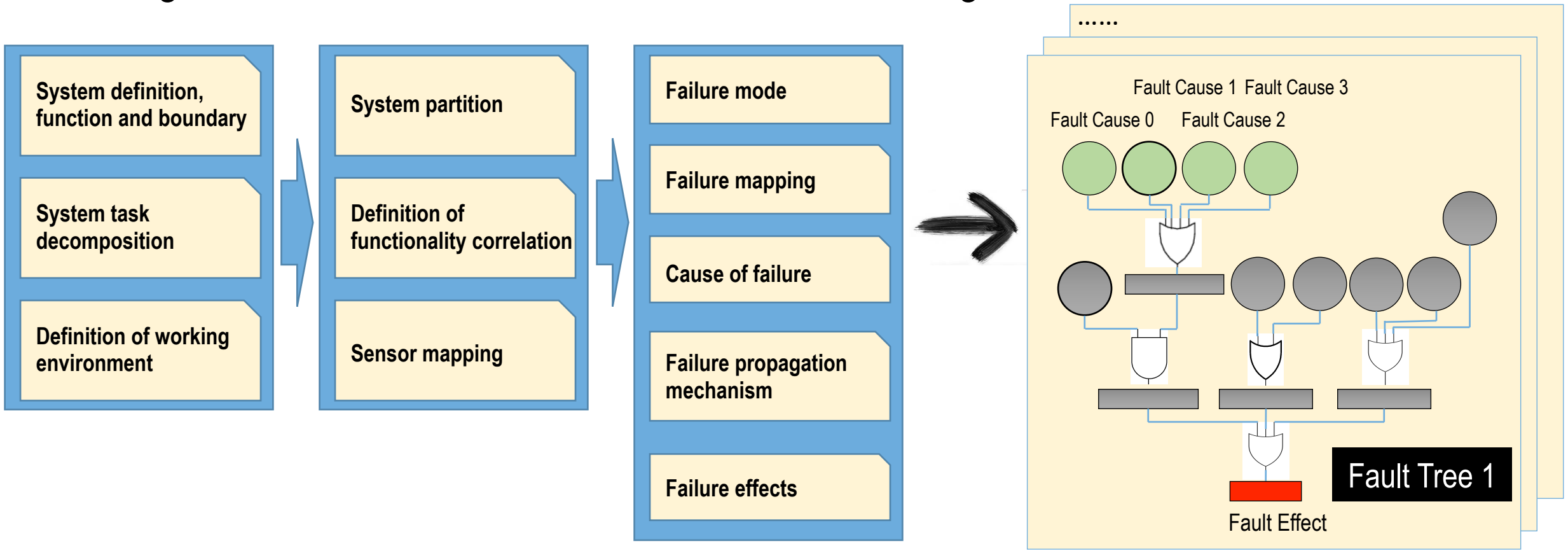


Outline

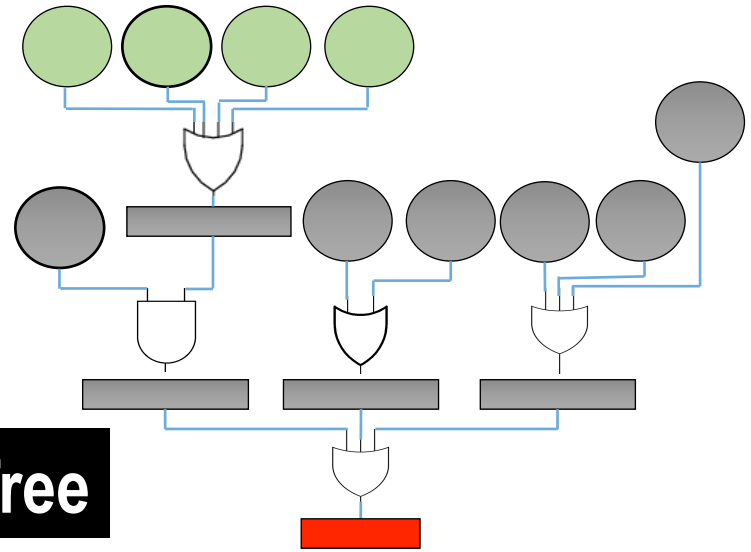
- The High Speed Train Sustainability Problem
- Problem Characteristics
- Ongoing works
- Conclusion

Failure Mode, Effect and Criticality Analysis (FMECA)

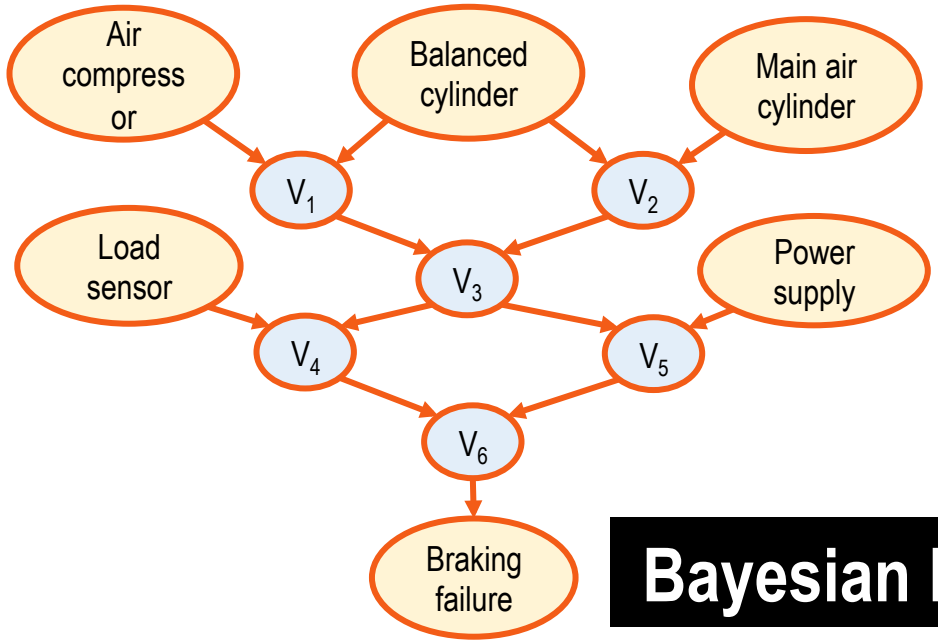
- Digitized reconstruction of EMU domain knowledge



Fault Tree vs. Bayesian Network



Fault Tree

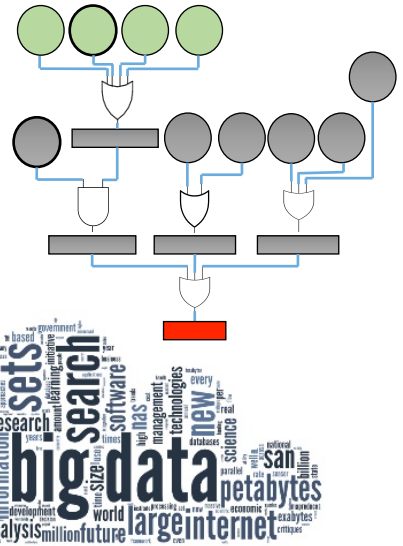


Bayesian Network

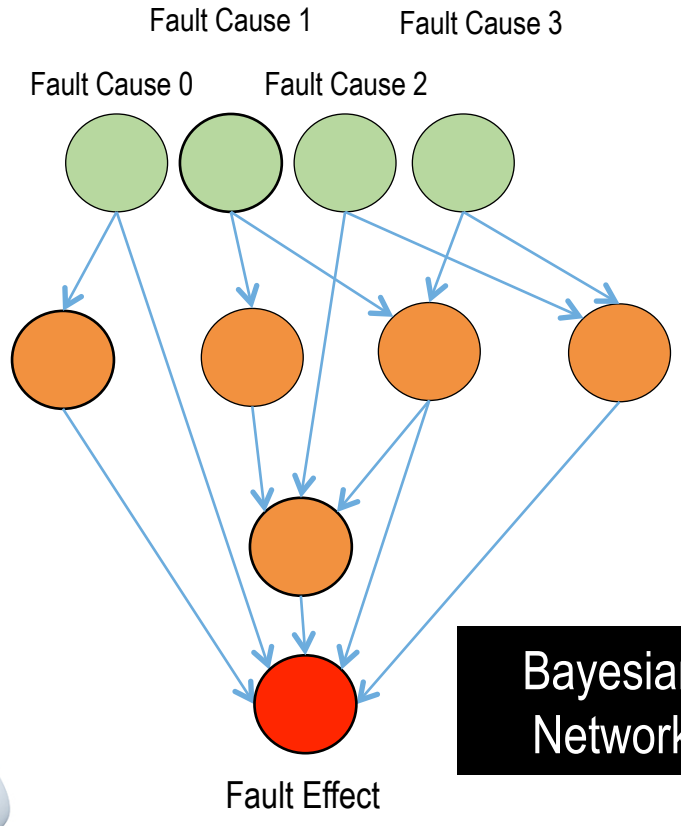
- **Subjective, uncertain (incomplete and ambiguous)**
- **But a primitive prior**

- **Learning from data to reduce subjectivity and uncertainty**
- **Natural to handle uncertainty**

Bayesian Computation for High Speed Train



Training

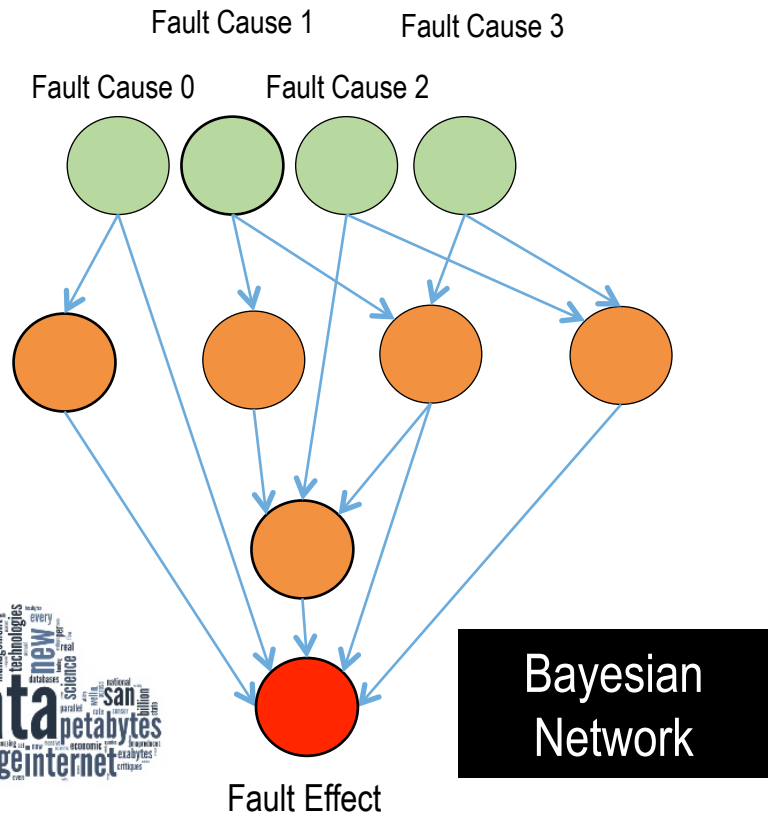


Bayesian Network

Diagnosis : P(cause|evidence) = ?
Prediction : P(effect|evidence) = ?
Learning : $\max_m P(model|data) = ?$
Decision : $\max_s P(solution|data) = ?$

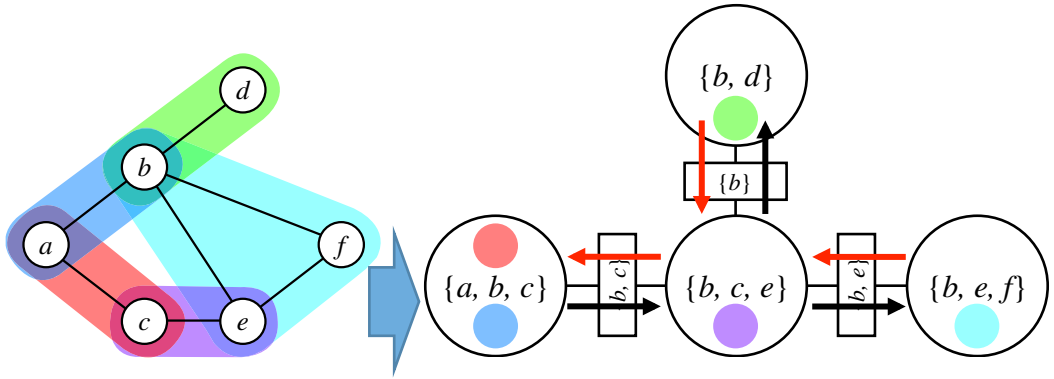
Bayesian Computation: Pros and Cons

- Pros
  - Natural to handle uncertainty
  - Elegant formulation of various problems
  - A unified framework for cognition
    - Human perception is a Bayesian process
  - Ability to learn from small dataset
    - Single case learning (Lake et al. Science 2015)
      - Compositionality, causality, and learning to learn
      - Applications in handwritten character classification
  - Strong momentum of probabilistic programming
- Cons
  - **SLOW!**
    - 60-node network takes days to learn
    - Learning is somehow clumsy

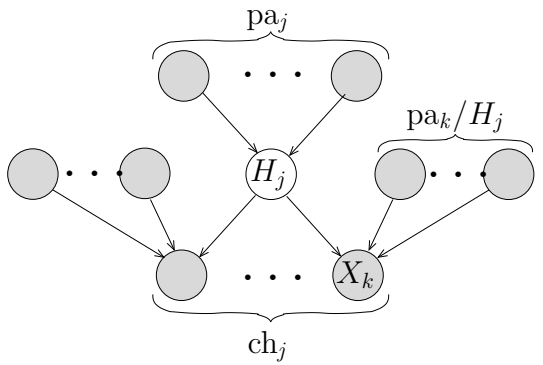


GPU Accelerated Bayesian Inference

- Caffe for Bayesian inference
  - Sparse models: Junction tree
    - BN ➔Junction tree (clique tree)
    - Parallel message passing

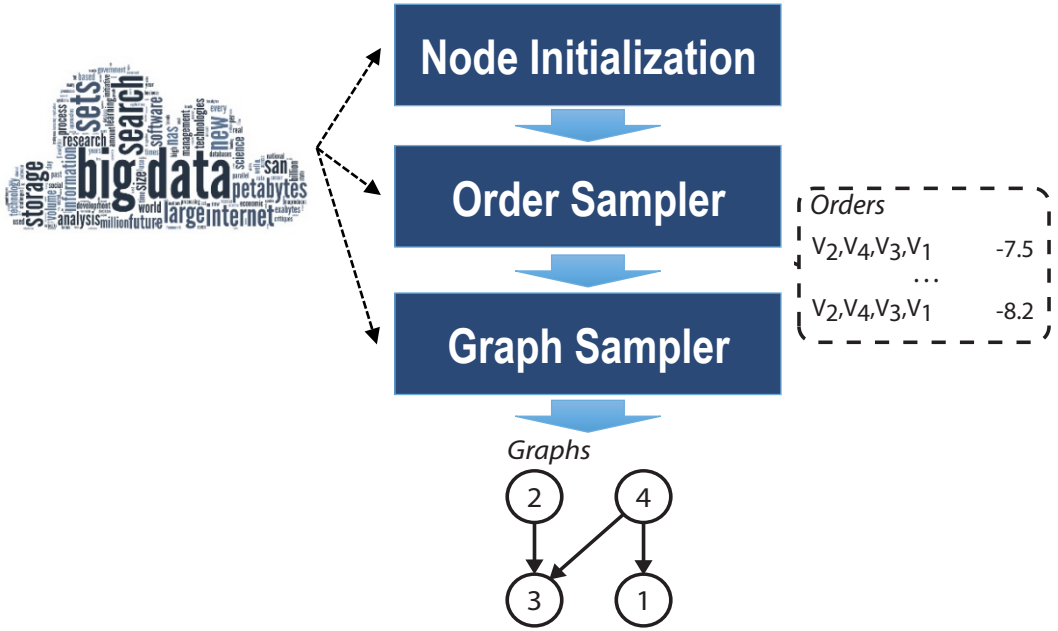


- Approximation algorithm: Variational method
  - Find approximate joint distribution Q(x;θ) over hidden variables x to approximate the true joint P(x)
  - Also can be message passing based

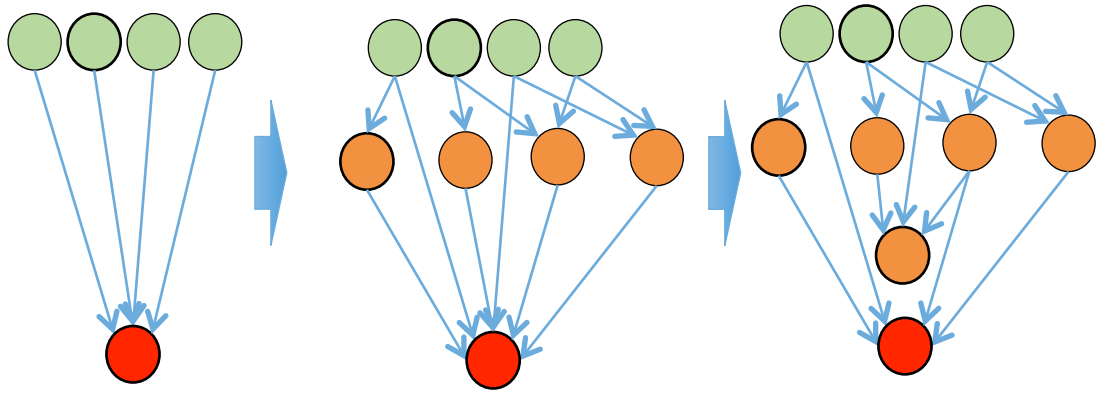


GPU Accelerated Bayesian Learning

- Caffe for Bayesian learning (structure learning)
  - Monte Carlo Markov Chain (MCMC)
    - Random sampling for local ordering
    - Then sampling for posterior distribution

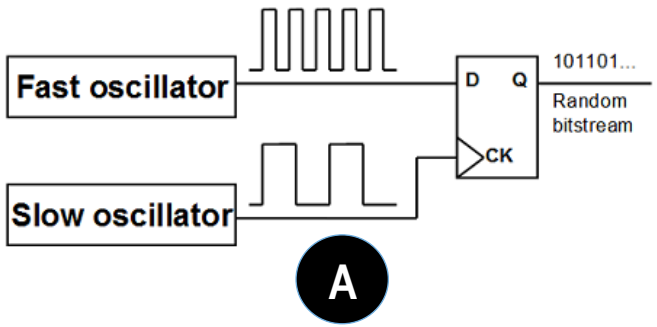


  - Incremental learning?
    - The solution space is huge
      - MCMC can be clumsy
    - Incrementally grow hidden variables?

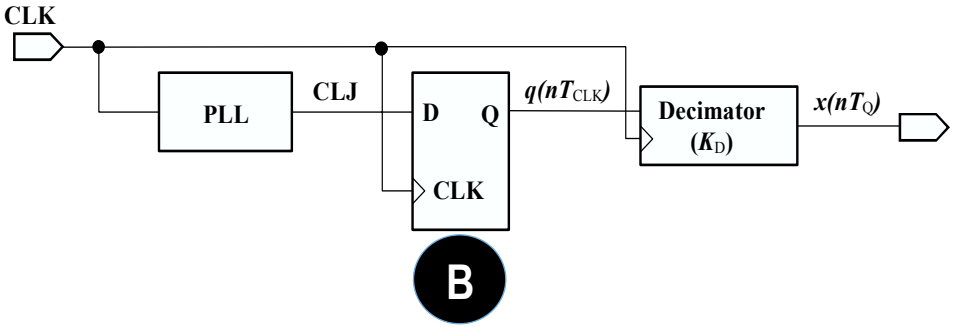


Bayesian Computer Architecture

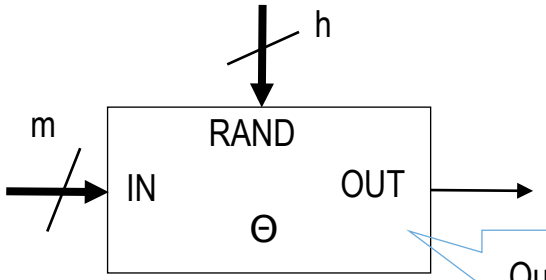
- Native support of statistical sampling
  - High throughput (true) random number generator
    - Sampling a fast oscillator (inverter chain) with a slow one **A**
    - Sampling analog noise of PLL **B**
  - Probability calculation
    - Stochastic logic gate, i.e. Θ-gate
      - Proposed by Mansinghka et al., 2008 **C**



A



B



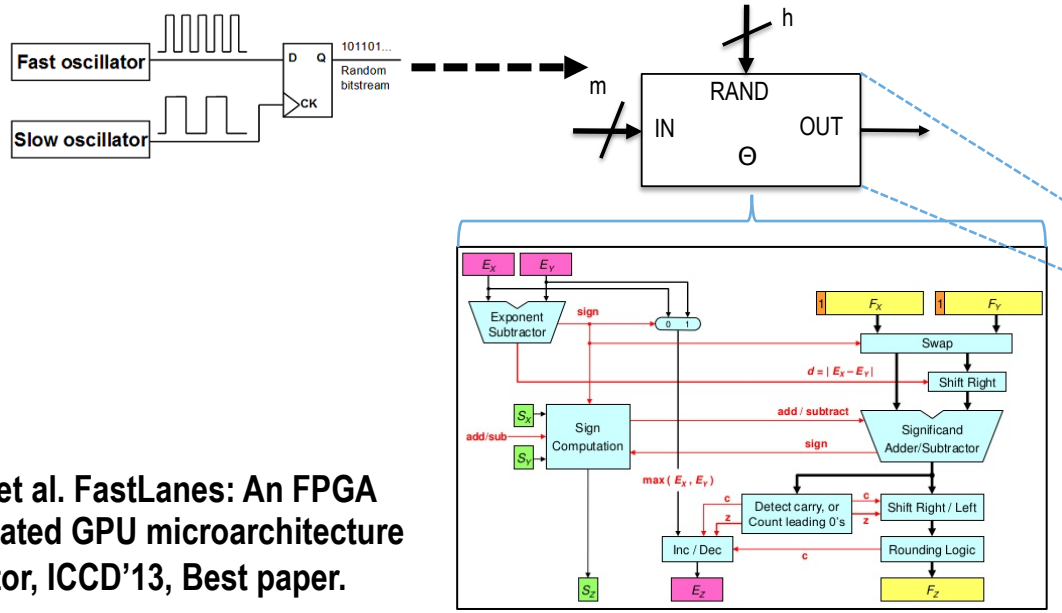
Out = 1 if
RAND <= IN

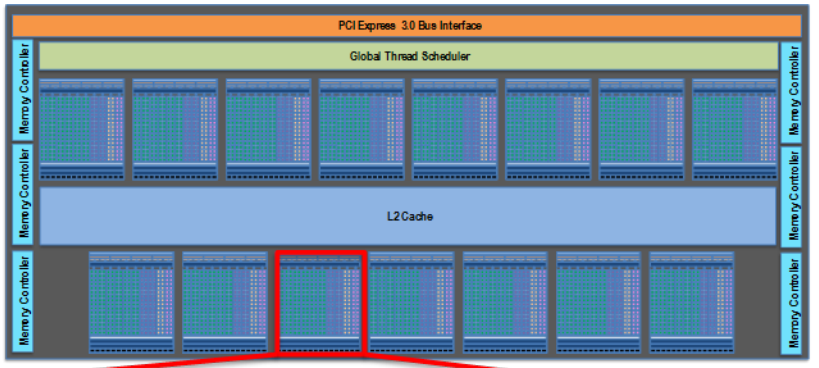
IN	OUT	P
0 0 0 0	0	1
0 0 0 0	1	0
0 0 0 1	0	15/16
0 0 0 1	1	1/16
…	…	…
1 1 1 1	0	1/16
1 1 1 1	1	15/16

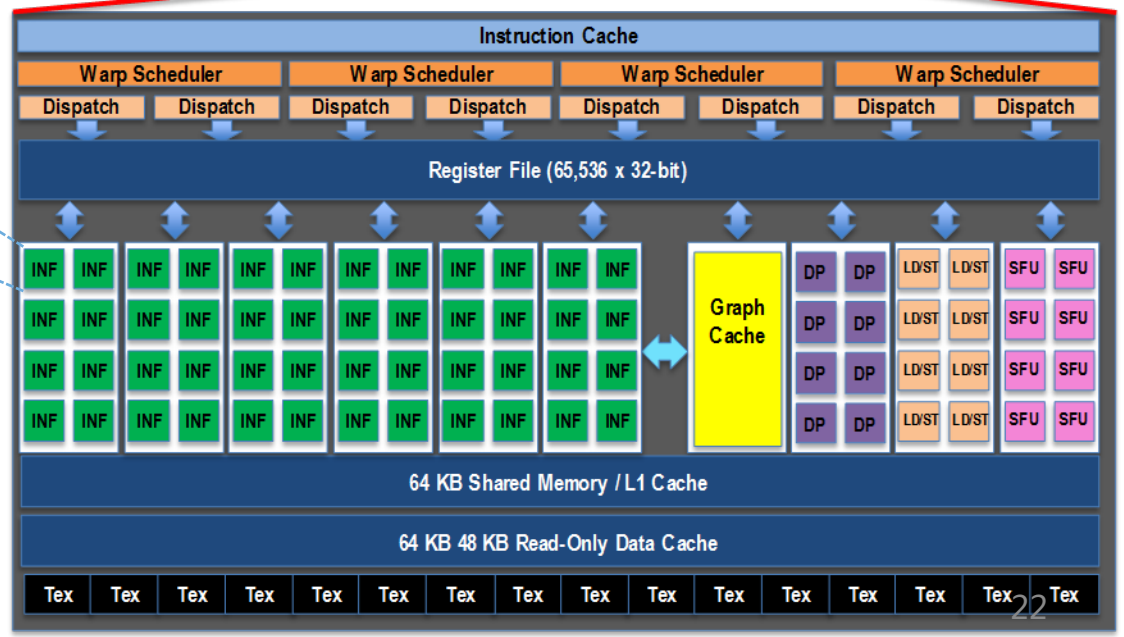
C

Bayesian Computer Architecture and Prototyping

- Leveraging the tools of GPUs (e.g. CUDA)
  - But may adopt light weight MIMD for higher computing throughput
- Prototyping with an FPGA based GPU simulator[1]







[1]Fang, et al. FastLanes: An FPGA accelerated GPU microarchitecture simulator, ICCD'13, Best paper.

Outline

- The High Speed Train Sustainability Problem
- Problem Characteristics
- Ongoing works
- Conclusion

Conclusion

- Inspired by "the High Speed Train Sustainability Problem"
- Bayesian based inference, learning and acceleration
  - Algorithms, parallel acceleration, and hardware microarchitectures
- But way more than high speed railway
  - Bioinformatics, communication theory, statistical physics, cognition, signal and image processing, information retrieval, statistical machine learning, …